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HEAT TRANSFER IN AMMONIA CONDENSERS

PART II

BY

ALONZO P. KRATZ
HORACE J. MACINTIRE
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UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

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DECEMBER, 1928

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PART II

BY

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HEAT TRANSFER IN AMMONIA CONDENSERS

PART II

I. INTRODUCTION

1. *Preliminary Statement.*—The tests reported in this bulletin constitute a continuation of the investigation of the heat transfer in ammonia condensers, the first results of which were embodied in Engineering Experiment Station Bulletin No. 171. Bulletin No. 171 dealt with the performance of three different types of ammonia condensers, namely, the atmospheric-bleeder, the double-pipe, and the vertical shell-and-tube; this bulletin comprises a study of the effect of certain changes in the condensing surface of the vertical shell-and-tube condenser, and an extension of the investigation to include a study of the heat transfer in the double-pipe superheat remover used in connection with the previous tests on the shell-and-tube condenser.

2. *Objects of Investigation.*—The two principal objects of this investigation may be stated briefly as follows:

(1) To determine the effect of reducing the condensing surface of the shell-and-tube condenser, first by decreasing the length of the condenser tubes, and second by reducing the number of effective tubes.

(2) To determine the coefficient of heat transfer for the double-pipe type of superheat remover.

3. *Acknowledgments.*—These tests have been part of the work of the Engineering Experiment Station of the University of Illinois, of which DEAN M. S. KETCHUM is the director, and of the Department of Mechanical Engineering, of which PROF. A. C. WILLARD is the head.

II. TESTS ON VERTICAL SHELL-AND-TUBE CONDENSER

4. *Description of Apparatus.*—The condenser used for these tests was a 10-ton vertical shell-and-tube condenser consisting of a shell 20 inches in diameter containing thirty 2-inch tubes 16 feet long. The ammonia was supplied by means of a 7½-inch by 10-inch twin vertical, single-acting, open-frame compressor driven by a Corliss engine at a constant speed. The condenser and plant, together with the testing apparatus, have been described in Engineering Experiment Station Bulletin No. 171.

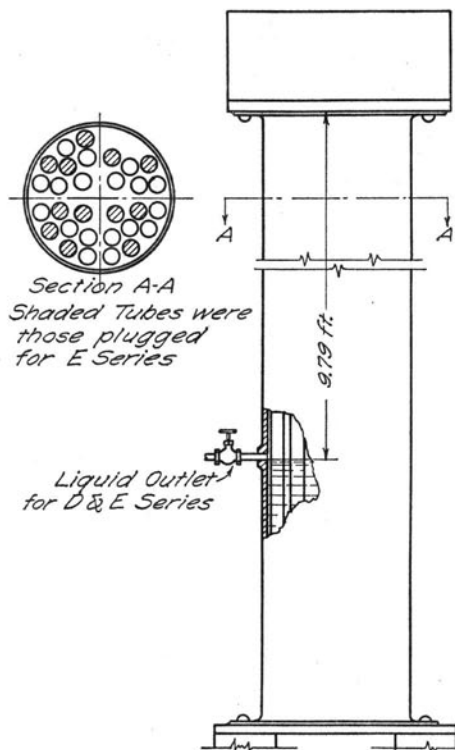


FIG. 1. DIAGRAM OF SHELL-AND-TUBE
CONDENSER

In the first series of tests the full effective condensing surface of 251 sq. ft. was utilized. For the second series the level of the liquid ammonia in the lower part of the shell was maintained at a height of 6.21 ft. by means of a drain pipe as shown in Fig. 1, thus blocking off the lower portion of the tubes and rendering the surface ineffective for condensing. The effective length of tubes was, therefore, 9.79 ft., and the effective condensing surface was 154 sq. ft. For the third series the liquid level was retained at a height of 6.21 ft. from the bottom of the shell, and, in addition, the twelve tubes indicated in the diagram in Fig. 1 were blocked by driving a solid plug in the top of each tube. This prevented the circulation of water in the tubes involved, and still further reduced the effective surface to 92.3 sq. ft.

Some rearrangement of the thermocouples for measuring the temperatures of the water was necessary when the effective surface was reduced, but no essential changes in the apparatus were made.

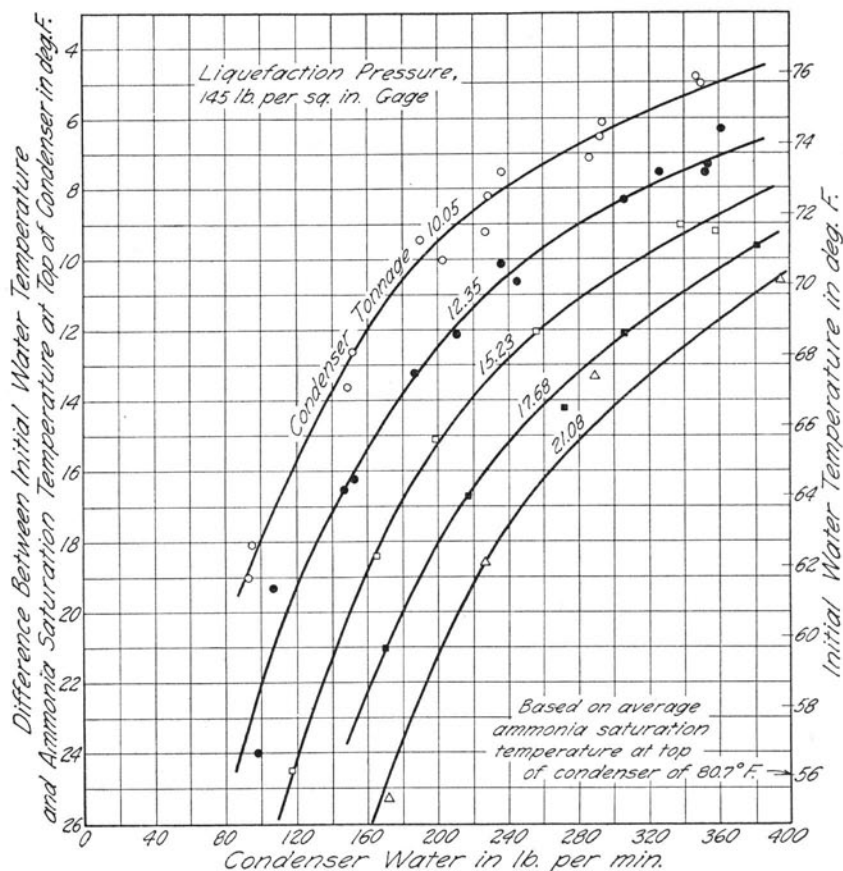


FIG. 2. INITIAL WATER TEMPERATURE FOR DIFFERENT TONNAGES AND WATER RATES IN C SERIES OF SHELL-AND-TUBE CONDENSER

5. *Method of Conducting Tests.*—The method of conducting tests and controlling conditions has been fully described in Engineering Experiment Station Bulletin No. 171.

6. *Results of Tests with Total Condensing Surface Effective.*—This series of tests has been designated as Series C and was discussed at length in Bulletin No. 171. The superheat was removed in a separate superheat remover and the ammonia gas was practically saturated when it entered the condenser. No liquid was allowed to accumulate on the lower tube sheet, and the total outside surface of the tubes was exposed to ammonia vapor, and was therefore effective condensing surface. This total surface had an area of 251 sq. ft.

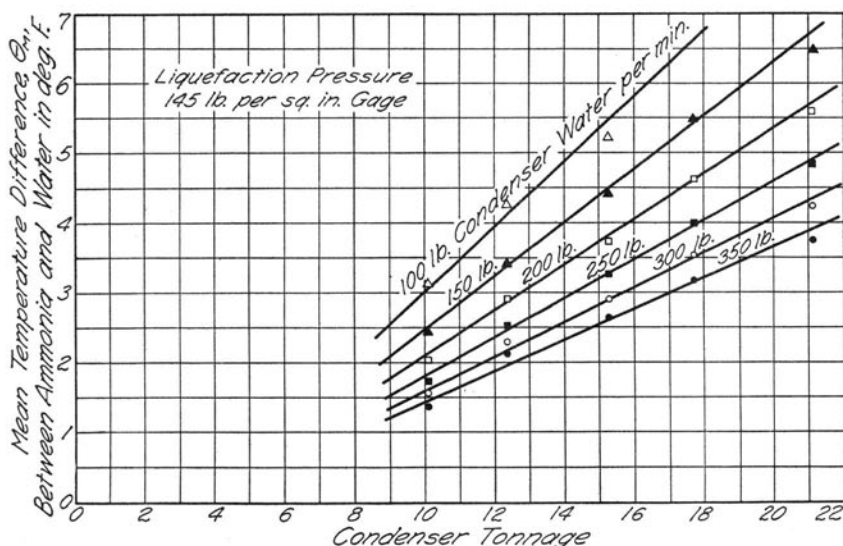


FIG. 3. MEAN TEMPERATURE DIFFERENCE BETWEEN AMMONIA AND WATER FOR DIFFERENT TONNAGES AND WATER RATES IN C SERIES OF SHELL-AND-TUBE CONDENSER

Since no correction for splash or spray thrown from the tube surfaces was necessary, the condenser water per minute was obtained directly from the total water weighed.

The condenser tonnage was computed from the formula

$$T = \frac{N(i'' - i')}{200} \quad (1)$$

in which T = condenser tonnage

N = ammonia condensed, lb. per min.

i'' = heat content of dry saturated ammonia vapor at the temperature of liquefaction in the condenser, B.t.u. per lb.

i' = heat content of the liquid at the temperature of the liquid leaving the condenser, B.t.u. per lb.

No sub-cooling of the liquid was observed, and the temperature of the liquid leaving the condenser was practically always the same as the saturation temperature for the ammonia.

Figure 2 was plotted directly from the results of individual tests, and shows the relations between the water rate, the initial temperature of the water, and the rate of condensation or condenser tonnage.

The mean temperature difference between the ammonia and the water, θ_m , was obtained by the method discussed in Bulletin No. 171.

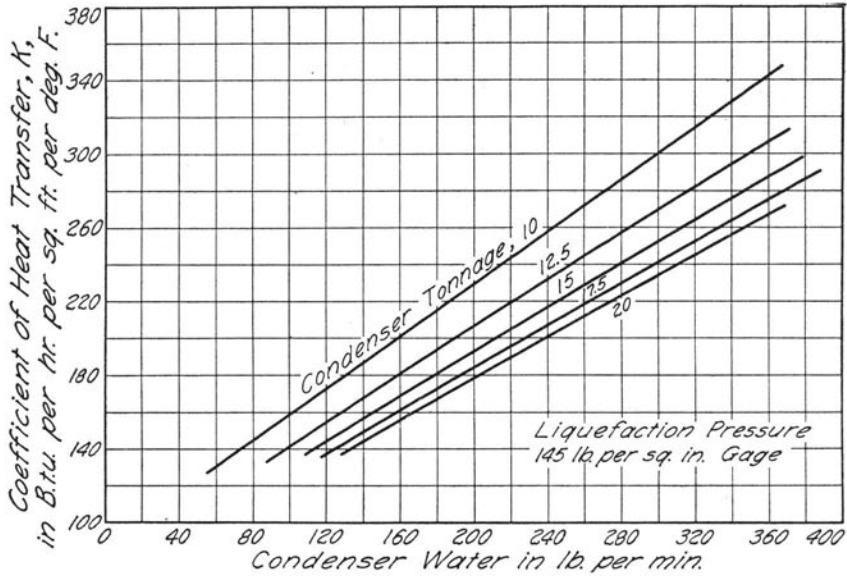


FIG. 4. COEFFICIENT OF HEAT TRANSFER FOR C SERIES OF SHELL-AND-TUBE CONDENSER

The curves showing the relations between θ_m , the condenser tonnage, and the water rate are given in Fig. 3. These curves have not been extended below the range of the observed data, because their shape in this region is more or less indeterminate, although it is probable that the curvature is such that they all pass through the origin.

The curves for the coefficient of heat transfer shown in Fig. 4 have been derived from those in Fig. 3 by making use of the formula

$$K = \frac{60 N (i'' - i')}{A \theta_m} \quad (2)$$

in which K = average coefficient of heat transfer, or the B.t.u. transmitted per sq. ft. per hr. per deg. difference in temperature.

N = ammonia condensed, lb. per min.

i'' = heat content of dry saturated ammonia vapor at the temperature of liquefaction, B.t.u. per lb.

i' = heat content of the liquid at the temperature of the liquid leaving the condenser, B.t.u. per lb.

A = effective condensing surface, sq. ft.

θ_m = mean temperature difference between the ammonia and the cooling water, deg. F.

TABLE No. 1
PRINCIPAL RESULTS OF TESTS ON SHELL-AND-TUBE CONDENSER
Series D

Test No.	Ammonia lb. per min.	Condenser Tonnage	Average Ammonia Saturation Temperature deg. F.	Final Liquid Ammonia Temperature deg. F.	Wetted Area sq. ft.	Condenser Water lb. per min.	Condenser Water gal. per min. per sq. ft.	Initial Water Temperature deg. F.
1	2	3	4	5	6	7	8	9
1D	4.17	10.43	82.1	81.6	154	91	0.071	57.7
2D	4.17	10.43	82.6	82.1	"	123	0.096	62.9
3D	4.26	10.65	82.2	81.8	"	153	0.111	66.8
4D	4.21	10.53	81.6	81.3	"	187	0.146	69.0
5D	4.15	10.38	81.8	81.6	"	198	0.154	70.1
6D	4.18	10.45	82.1	81.4	"	229	0.185	71.3
7D	4.21	10.53	82.2	81.8	"	250	0.195	72.1
8D	4.26	10.65	82.0	81.6	"	288	0.225	73.0
9D	4.15	10.38	82.2	81.7	"	322	0.251	73.8
10D	4.15	10.38	81.9	81.7	"	346	0.270	74.5
11D	4.12	10.30	81.7	81.7	"	391	0.304	75.6
12D	5.12	12.80	81.3	80.2	"	135	0.105	60.7
13D	5.09	12.73	81.3	80.6	"	160	0.125	64.0
14D	5.18	12.95	81.7	81.1	"	177	0.138	65.5
15D	5.07	12.63	81.5	81.4	"	197	0.153	67.2
16D	5.09	12.73	82.1	81.5	"	228	0.178	69.5
17D	5.01	12.53	80.8	81.2	"	256	0.200	69.3
18D	4.94	12.35	81.0	81.4	"	274	0.214	70.4
19D	5.00	12.50	80.8	81.4	"	308	0.241	71.3
20D	4.96	12.40	80.8	81.3	"	325	0.254	71.7
21D	4.90	12.25	80.7	81.5	"	360	0.282	72.7
22D	5.90	14.75	81.4	81.3	"	151	0.118	60.9
23D	5.97	14.93	81.4	81.3	"	176	0.137	63.3
24D	5.86	14.65	81.1	81.2	"	196	0.153	65.1
25D	6.06	15.15	81.3	81.7	"	222	0.173	67.2
26D	6.25	15.63	81.5	81.7	"	254	0.199	68.1
27D	6.09	15.23	81.1	81.4	"	252	0.188	68.2
28D	6.00	15.00	81.1	81.7	"	305	0.238	70.4
29D	5.98	14.95	81.2	81.6	"	322	0.252	71.1
30D	6.05	15.13	81.1	81.8	"	354	0.276	71.4
31D	6.99	17.73	81.3	81.8	"	148	0.116	56.3
32D	7.12	17.80	81.5	81.8	"	182	0.142	60.3
33D	6.90	17.25	81.0	81.5	"	199	0.156	61.8
34D	6.75	16.88	80.9	81.0	"	229	0.179	65.4
35D	6.88	17.20	81.2	81.6	"	247	0.193	66.7
36D	6.70	16.75	81.1	81.6	"	272	0.212	68.0
37D	6.80	17.00	81.4	81.6	"	303	0.236	69.5
38D	6.61	16.53	81.0	81.1	"	335	0.262	70.6
39D	6.78	16.95	81.8	81.6	"	361	0.282	71.8
40D	8.14	20.35	81.7	82.0	"	205	0.160	60.1
41D	8.28	20.70	82.0	82.2	"	232	0.181	62.5
42D	8.39	20.98	82.3	82.3	"	251	0.197	63.8
43D	7.92	19.80	81.8	81.7	"	278	0.217	65.9
44D	7.95	19.88	82.1	81.9	"	301	0.235	66.6
45D	8.20	20.50	82.2	81.8	"	328	0.256	67.6
46D	8.25	20.63	82.6	82.3	"	351	0.274	68.5

It may be noted that at a constant water rate the value of K decreases as the condenser tonnages increase, thus indicating decreasing values of K with increasing values of θ_m . Therefore, in this condenser the thickness of the layer of liquid ammonia adhering to the surfaces of the tubes must increase at such a rate that its resistance to the flow of heat more than offsets the tendency for K to increase as θ_m

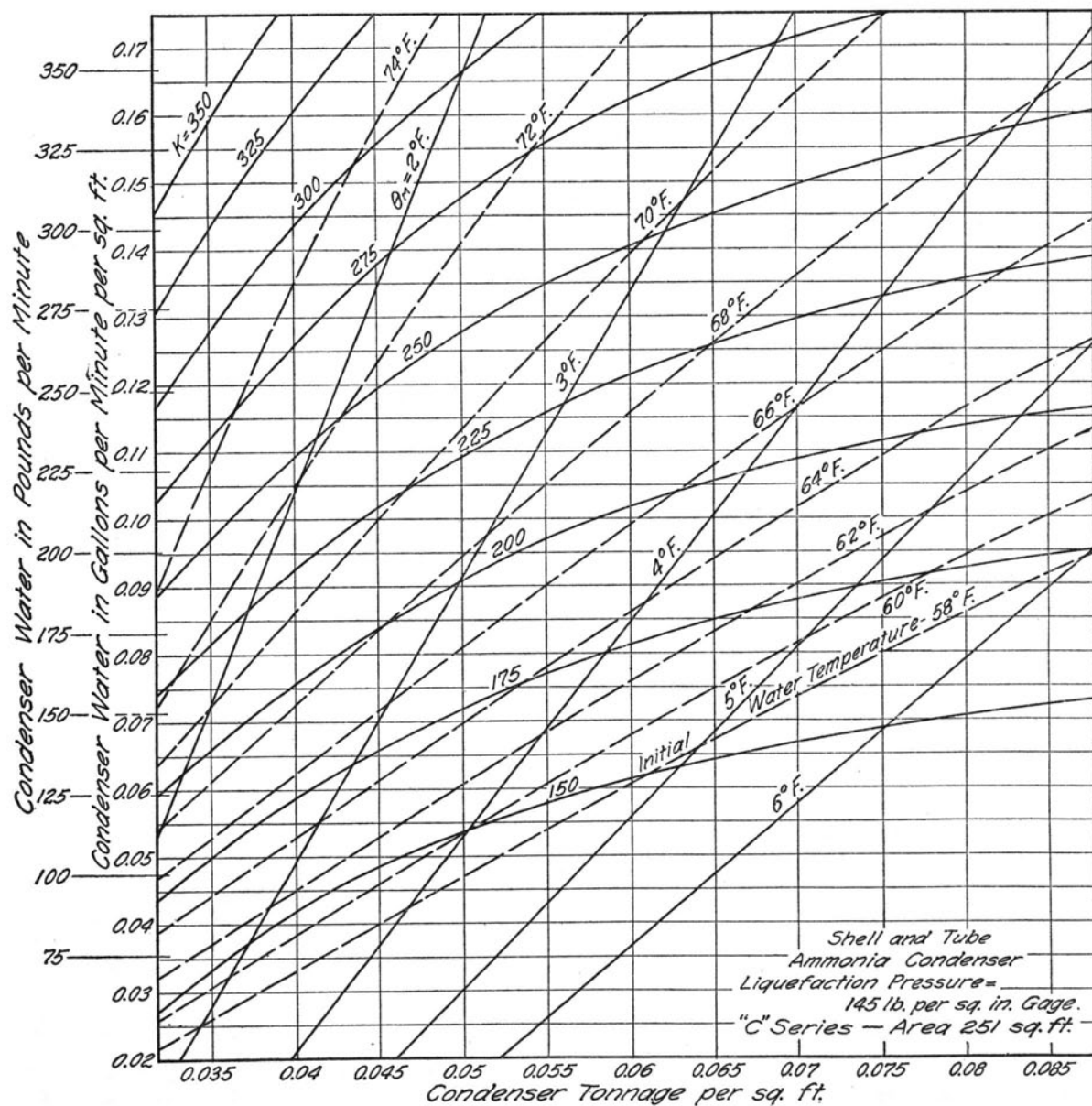


FIG. 5. PERFORMANCE CHART FOR C SERIES OF SHELL-AND-TUBE CONDENSER

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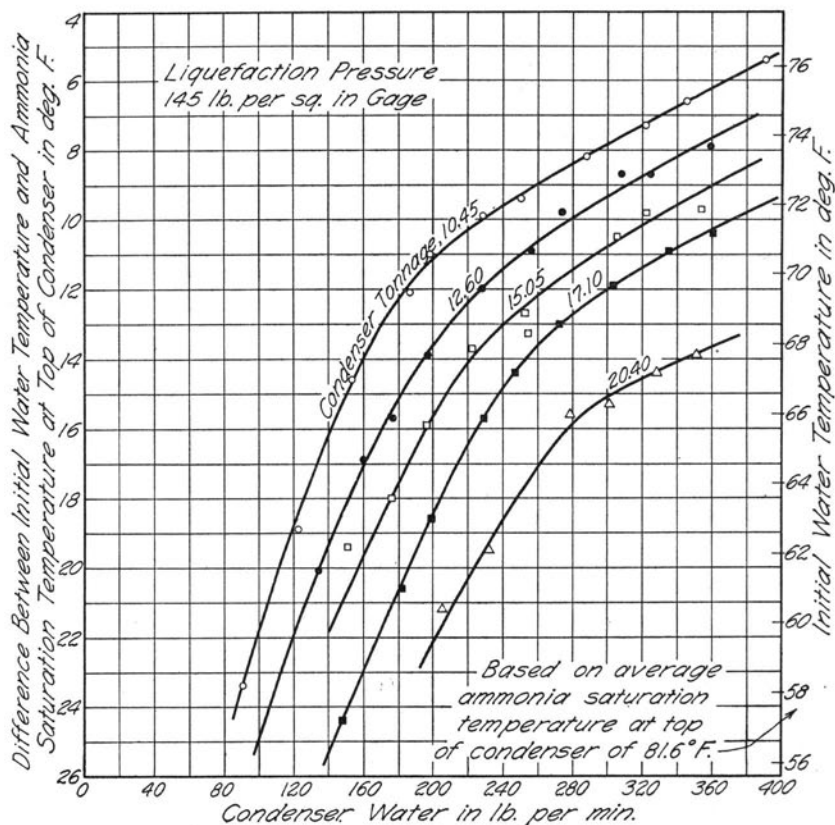


FIG. 6. INITIAL WATER TEMPERATURES FOR DIFFERENT TONNAGES AND WATER RATES IN D SERIES OF SHELL-AND-TUBE CONDENSER

becomes greater. This same phenomenon may be observed when steam is condensed in a surface condenser.*

The performance chart shown in Fig. 5 was obtained by combining the curves shown in Figs. 2, 3, and 4 with Equation (2). As an example of the use of this chart, it may be noted that when 0.15 gal. of cooling water having an initial temperature of 68 deg. F. were used per sq. ft. of surface per min. a condenser tonnage of 0.077 per sq. ft. was developed. The mean temperature difference between the ammonia and the water was 3.8 deg. F., and the heat transmitted per sq. ft. of surface per deg. F. per hr. was 245 B.t.u.

*George A. Orrok. "Transmission of Heat in Surface Condensation" Trans. A.S.M.E. Vol. 32, p. 1139, 1910.

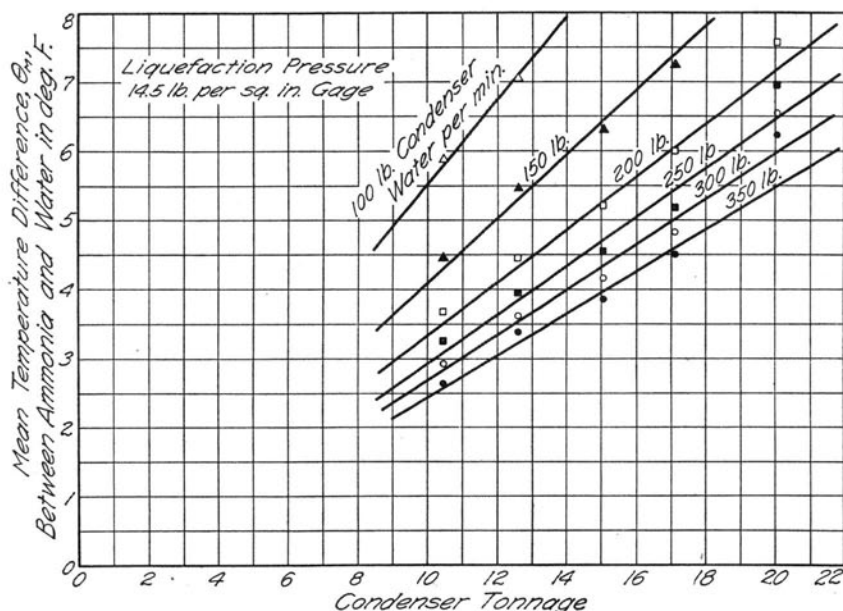


FIG. 7. MEAN TEMPERATURE DIFFERENCE BETWEEN AMMONIA AND WATER FOR DIFFERENT TONNAGES AND WATER RATES IN D SERIES OF SHELL-AND-TUBE CONDENSER

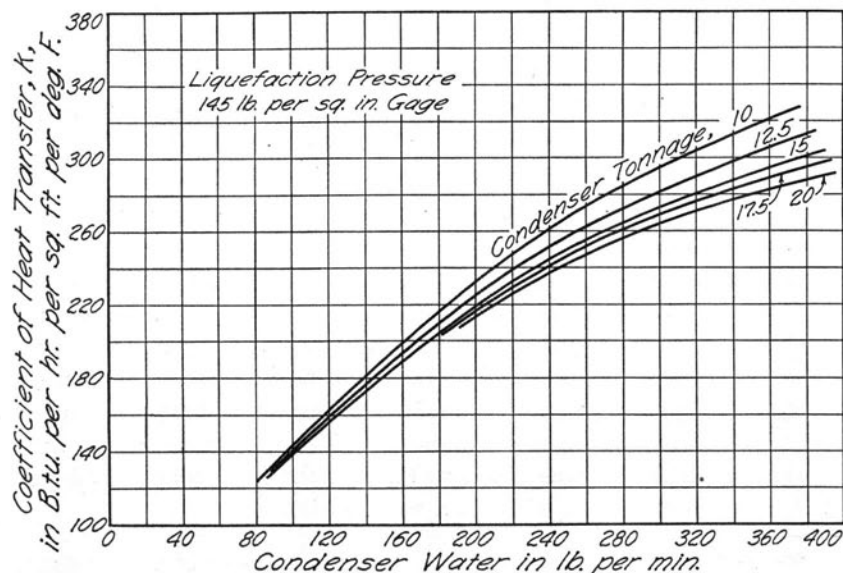


FIG. 8. COEFFICIENT OF HEAT TRANSFER FOR D SERIES OF SHELL-AND-TUBE CONDENSER

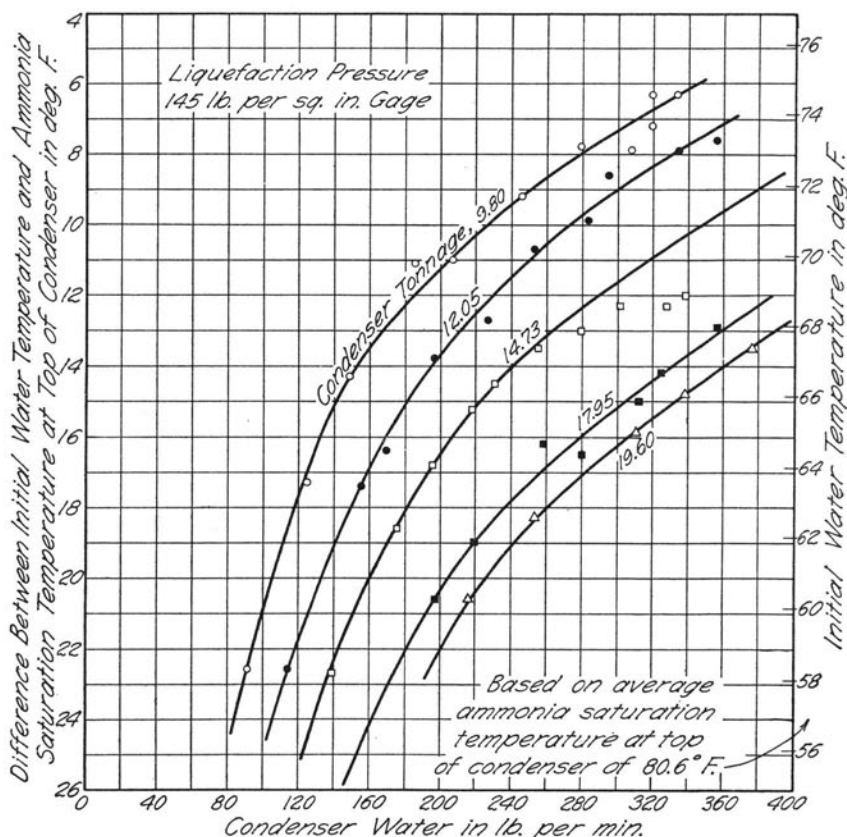


FIG. 10. INITIAL WATER TEMPERATURES FOR DIFFERENT TONNAGES AND WATER RATES IN E SERIES OF SHELL-AND-TUBE CONDENSER

Since no means were available for weighing condensate from different parts of the surface of this condenser, no direct comparison of the effectiveness of different sections of the condenser can be made for this series of tests. It was observed, however, that the maximum condensation, as indicated by the rate of increase in the temperature of the cooling water, occurred within 6 ft. of the top of the shell, and that the difference in temperature between the ammonia and the water became only about 1.5 deg. F. at a distance of approximately 9.5 ft. from the upper tube sheet. This distance varied somewhat with the water rate and rate of condensation, but the condition seemed to present evidence that the lower part of the condenser was relatively ineffective, and suggested the possibility that the surface could be reduced without materially altering the performance of the condenser.

TABLE NO. 2
PRINCIPAL RESULTS OF TESTS ON SHELL-AND-TUBE CONDENSER
Series E

Test No.	Ammonia lb. per min.	Condenser Tonnage	Average Ammonia Saturation Temperature deg. F.	Final Liquid Ammonia Temperature deg. F.	Wetted Area sq. ft.	Condenser Water lb. per min.	Condenser Water gal. per min. per sq. ft.	Initial Water Temperature deg. F.
1	2	3	4	5	6	7	8	9
1E	7.80	19.50	82.3	81.4	92.3	216	0.281	61.1
2E	7.67	19.18	81.7	81.5	"	253	0.330	63.2
3E	8.02	20.05	82.3	82.1	"	274	0.357	64.2
4E	7.72	19.80	81.8	81.2	"	310	0.404	65.5
5E	7.90	19.75	81.8	81.3	"	338	0.440	66.5
6E	7.91	19.78	81.1	80.9	"	376	0.490	67.2
7E	7.24	18.10	82.3	82.0	"	197	0.256	60.8
8E	7.23	18.08	82.0	81.9	"	219	0.286	62.3
9E	6.99	17.48	82.0	81.7	"	258	0.336	65.1
10E	7.35	18.38	82.1	81.8	"	280	0.365	65.4
11E	7.21	18.03	82.3	82.2	"	312	0.406	67.1
12E	7.17	17.93	82.0	81.9	"	324	0.421	67.4
13E	7.06	17.45	82.2	81.8	"	356	0.464	68.9
14E	3.96	9.90	81.4	81.2	"	91	0.118	58.0
15E	4.05	10.13	81.9	80.6	"	124	0.161	63.6
16E	3.96	9.90	81.7	80.4	"	148	0.192	66.5
17E	3.86	9.45	81.3	80.2	"	185	0.241	69.3
18E	3.92	9.80	81.1	80.1	"	206	0.268	69.5
19E	3.84	9.60	80.7	80.9	"	245	0.318	70.9
20E	3.92	9.80	80.7	81.3	"	235	0.306	70.5
21E	3.89	9.73	80.7	81.2	"	279	0.363	72.2
22E	3.95	9.88	80.7	81.2	"	307	0.400	72.4
23E	3.86	9.65	80.7	81.5	"	319	0.415	73.1
24E	3.91	9.78	81.3	81.7	"	333	0.434	74.3
25E	4.80	12.00	80.6	81.2	"	114	0.148	57.6
26E	5.06	12.65	80.9	81.1	"	155	0.202	62.8
27E	4.94	12.35	80.8	81.2	"	169	0.220	64.4
28E	4.93	12.33	80.6	80.8	"	196	0.256	66.7
29E	4.75	11.88	80.4	80.7	"	226	0.294	67.7
30E	4.84	12.10	81.0	81.2	"	252	0.329	70.0
31E	4.72	11.80	80.6	80.8	"	283	0.368	70.7
32E	4.72	11.80	80.9	81.2	"	304	0.396	72.2
33E	4.69	11.73	80.4	80.8	"	334	0.435	72.4
34E	4.72	11.80	81.0	81.5	"	356	0.464	73.2
35E	5.93	14.83	81.2	80.9	"	138	0.179	57.9
36E	5.82	14.55	80.5	80.2	"	175	0.228	61.6
37E	5.85	14.63	80.8	80.1	"	195	0.254	63.8
38E	5.83	14.58	80.9	80.2	"	230	0.300	66.2
39E	5.78	14.45	80.3	79.6	"	254	0.331	66.6
40E	5.93	14.83	81.0	80.0	"	279	0.363	67.9
41E	5.93	14.83	81.1	80.1	"	301	0.392	69.0
42E	5.96	14.90	81.8	80.9	"	327	0.426	70.1
43E	5.98	14.95	81.5	80.5	"	348	0.454	70.5

Two additional series of tests, Series D and Series E, were accordingly run in order to determine the effect of reducing the effective surface.

7. *Results of Tests with Length of Tubes Reduced.*—The principal results from Series D are given in Table 1. From this table it may be noted that the total wetted surface was 154 sq. ft., and that the temperature of the liquid leaving the condenser was practically the same as the temperature of the saturated ammonia vapor. That is, no subcooling took place.

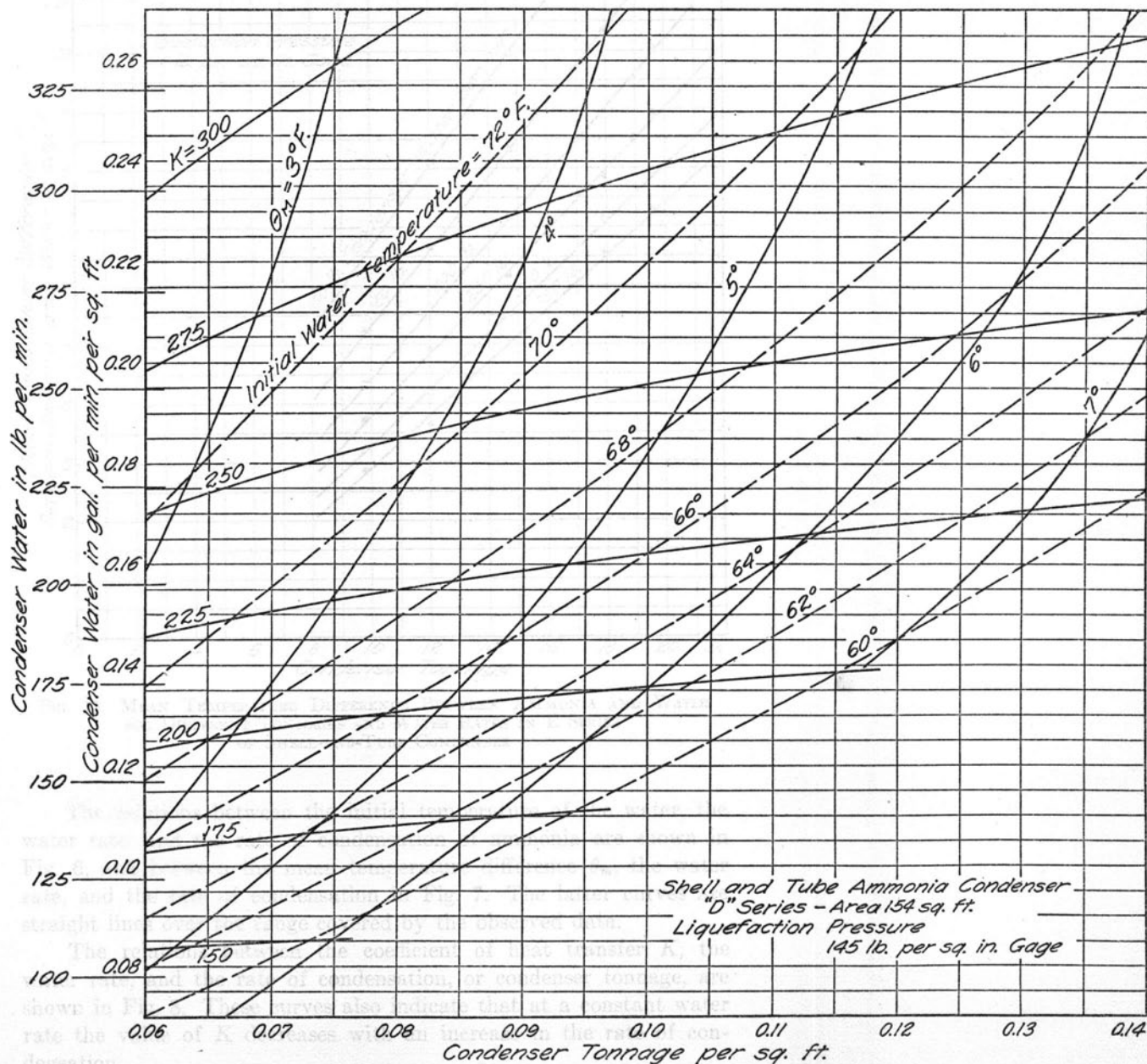


FIG. 9. PERFORMANCE CHART FOR D SERIES OF SHELL-AND-TUBE CONDENSER

From this chart it may be observed that when 0.15 gal. of cooling

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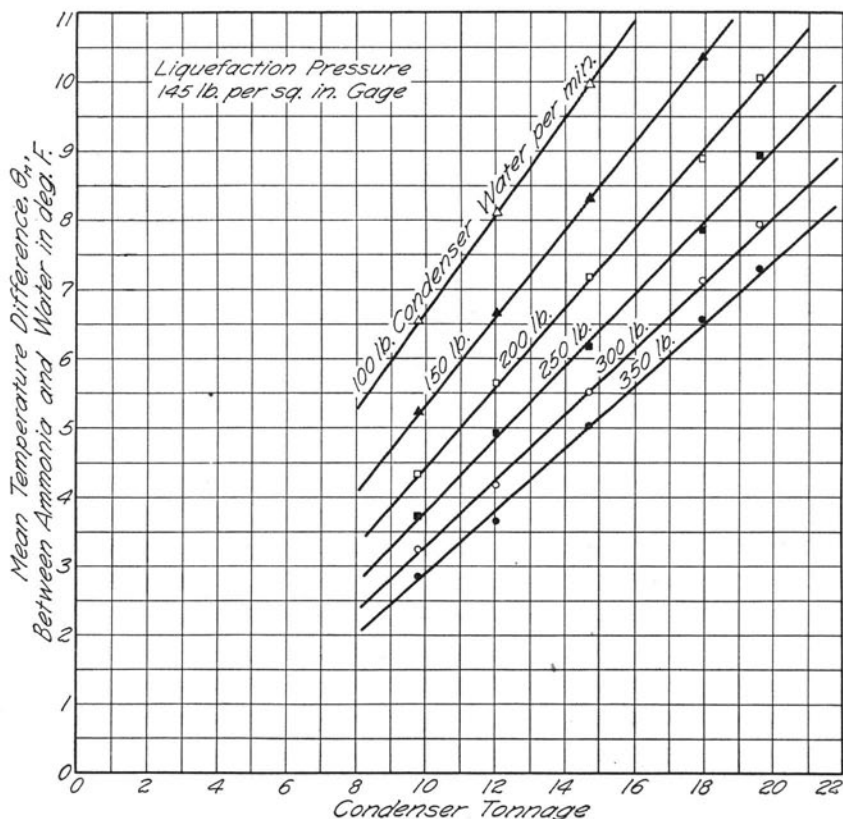


FIG. 11. MEAN TEMPERATURE DIFFERENCE BETWEEN AMMONIA AND WATER FOR DIFFERENT TONNAGES AND WATER RATES IN E SERIES OF SHELL-AND-TUBE CONDENSER

The relations between the initial temperature of the water, the water rate, and the rate of condensation of ammonia are shown in Fig. 6, and between the mean temperature difference θ_m , the water rate, and the rate of condensation in Fig. 7. The latter curves are straight lines over the range covered by the observed data.

The relations between the coefficient of heat transfer K , the water rate, and the rate of condensation, or condenser tonnage, are shown in Fig. 8. These curves also indicate that at a constant water rate the value of K decreases with an increase in the rate of condensation.

The complete performance chart for Series D is given in Fig. 9. From this chart it may be observed that when 0.15 gal. of cooling

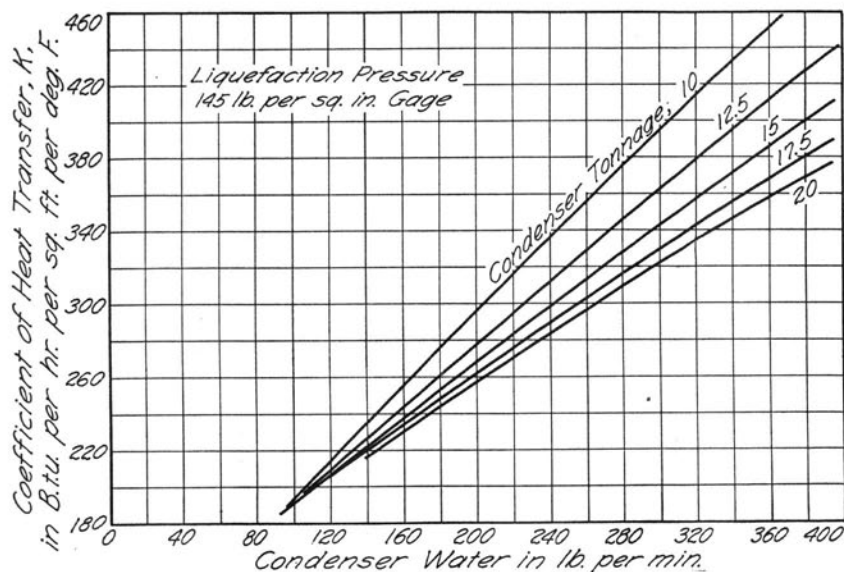


FIG. 12. COEFFICIENT OF HEAT TRANSFER FOR E SERIES OF SHELL-AND-TUBE CONDENSER

water, having an initial temperature of 68 deg. F. were used per sq. ft. per min., a condenser tonnage of 0.0804 per sq. ft. was developed. The mean temperature difference between the ammonia and the water was 4.38 deg. F., and the heat transmitted per sq. ft. of surface per deg. F. per hr. was 220 B.t.u.

8. *Results of Tests with Both Length and Number of Tubes Reduced.*—This series of tests has been designated as Series E, and the principal results are shown in Table 2. The total wetted surface was 92.3 sq. ft. The table also indicates that no subcooling of the liquid occurred, inasmuch as the temperature of the liquid leaving the condenser was practically the same as the temperature of the saturated ammonia vapor.

The relations between the initial temperature of the water, the water rate, and the rate of condensation are shown in Fig. 10. This is a family of curves presenting the same characteristics as those shown for Series C and D in Figs. 2 and 6. The relations between the mean temperature difference θ_m , the water rate, and the rate of condensation are shown in Fig. 11. These curves also indicate straight line relations over the range covered by the observed data.

The curves in Fig. 12 show the relations between the coefficient of heat transfer K , the water rate, and the rate of condensation or

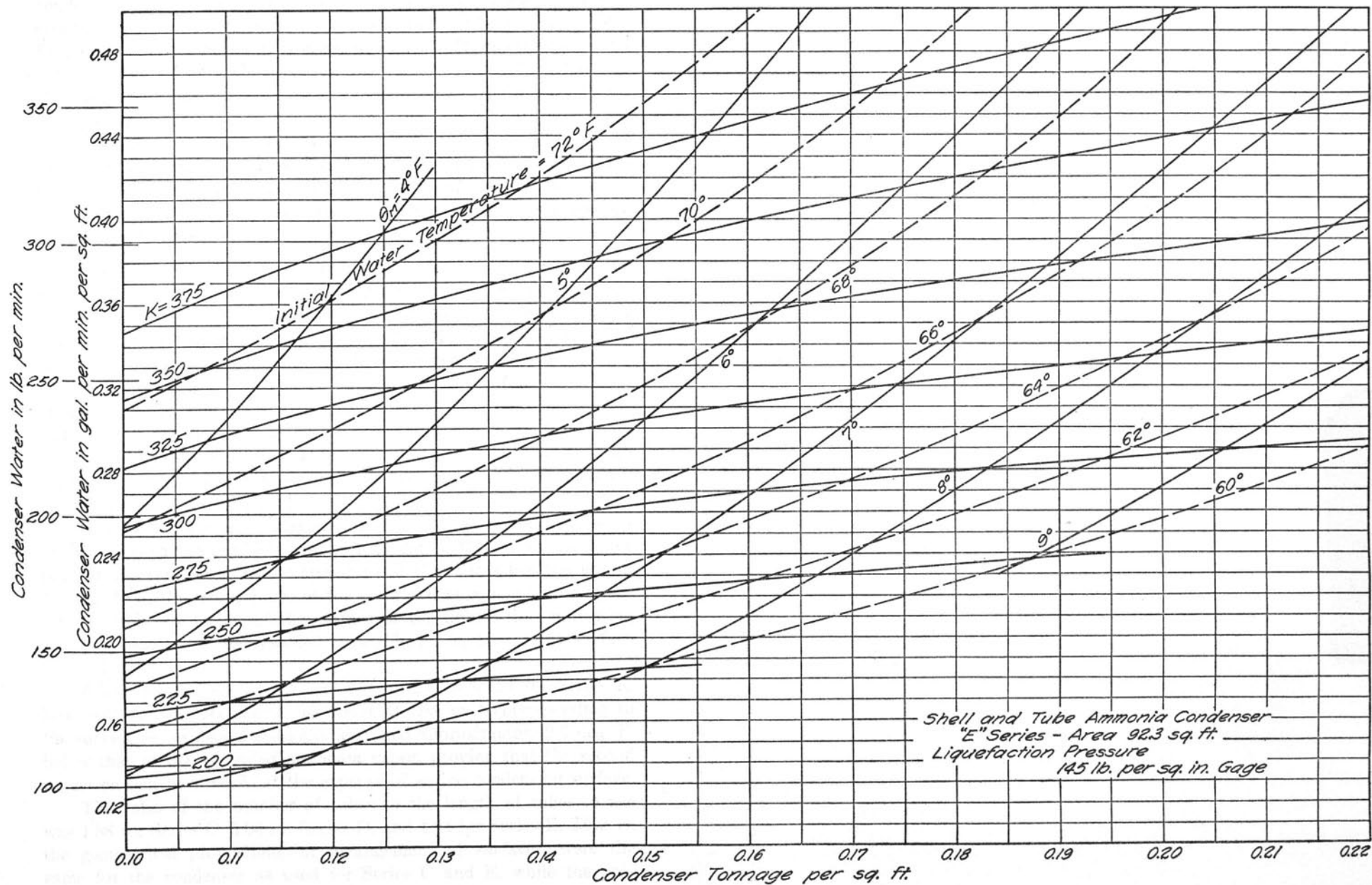


FIG. 13. PERFORMANCE CHART FOR E SERIES OF SHELL-AND-TUBE CONDENSER

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condenser tonnage. At a constant water rate the value of K decreases with increasing rates of condensation. The complete performance chart for Series E is given in Fig. 13. It was impossible to obtain points on this chart within the range covered by charts in Figs. 5 and 9, and hence no direct comparison can be made. As an example, however, it may be noted that when 0.22 gal. of cooling water having an initial temperature of 68 deg. F. were used per sq. ft. of surface per min. a condenser tonnage of 0.1064 per sq. ft. was developed. The mean difference between the ammonia and the water was 4.84 deg. F. and the heat transmitted per sq. ft. of surface per deg. F. per hr. was 264 B.t.u.

9. *Effect of Reducing the Amount of Condensing Surface.*—In Section 3 attention was directed to the fact that in Series C, where the total available condensing surface was in use, active condensation ceased in a plane approximately 9.5 ft. below the upper tube sheet of the condenser, as indicated by the fact that the temperature of the cooling water became practically the same as that of the saturated ammonia vapor when the water reached this plane, and no appreciable rise in the temperature of the water occurred in the lower portion of the condenser. With the available pump capacity and the available initial water temperatures, it was impossible to circulate enough water to lower this plane.

When the condensing surface was reduced, as it was for Series D, by allowing the liquid to rise to a height of 6.21 ft. in the lower part of the condenser, the temperature of the water became within 1.5 deg. F. of the temperature of the saturated ammonia vapor somewhere within six inches of the surface of the liquid, thus indicating that the active surface extended to within six inches of the surface of the liquid.

When the condensing surface was further reduced for Series E, however, the temperature of the water at the level corresponding to the surface of the liquid ammonia averaged approximately 2.5 deg. F. below that of the saturated ammonia vapor, proving that the second reduction had been made at the expense of active condensing surface.

The ratio of the number of tubes to the length of tubes in use was 1.88 for Series C, 3.06 for Series D, and 1.84 for Series E. That is, the geometrical proportions, or arrangement of surfaces, were the same for the condenser as used for Series C and E, while the proportions used for Series D were different from those used for Series C and E.

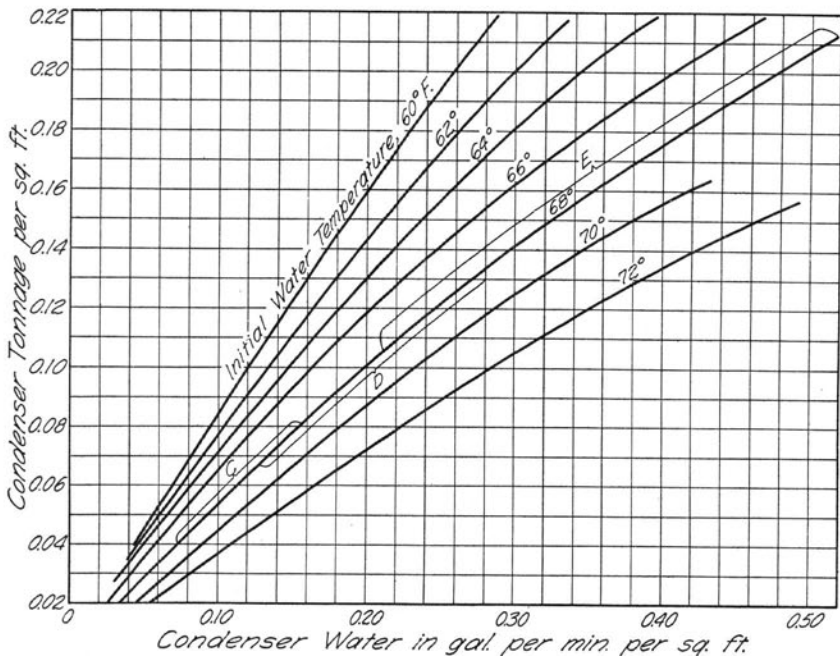


FIG. 14. CONDENSER WATER FOR DIFFERENT TONNAGES AND INITIAL WATER TEMPERATURES FOR C, D, AND E SERIES OF SHELL-AND-TUBE CONDENSER

The curves shown in Fig. 14 have been derived from the performance charts in Figs. 5, 9, and 13. The brackets extending along the curves for an initial water temperature of 68 deg. F. indicate the portions of the curves covered by the ranges of the three series of tests, respectively. From these curves it may be noted that the condenser tonnage per square foot of surface that can be obtained with a given volume of water circulated per square foot for any given initial temperature of the water can be represented over the whole range of tests covered by the three series by a family of smooth curves. This indicates that within the range of these tests the condenser tonnage per square foot is independent of the size of condenser or the arrangement of surface, and is a function only of the initial temperature of the water and the amount that can be passed over each square foot of surface in a unit of time.

In Fig. 15 the total condenser tonnage and the condenser tonnage per square foot of surface for the three series of tests on the shell-and-tube condenser have been plotted against the water rate in gallons per minute per square foot for an initial water temperature of

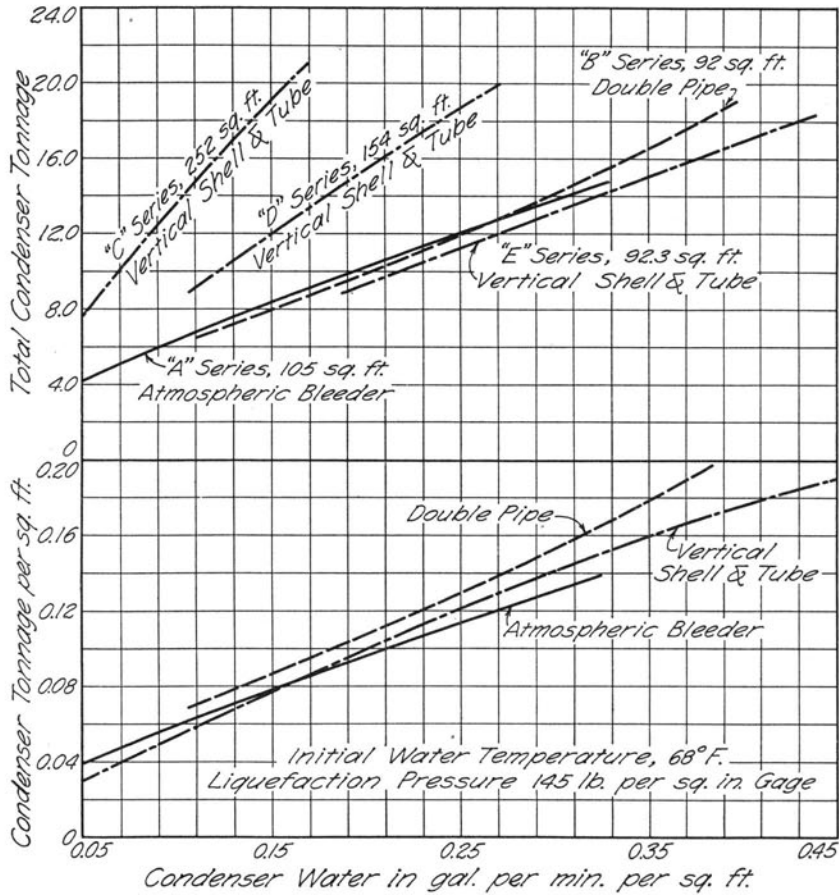


FIG. 15. COMPARISON OF THE PERFORMANCE OF THE ATMOSPHERIC BLEEDER, DOUBLE PIPE, AND SHELL-AND-TUBE AMMONIA CONDENSERS

68 deg. F. The corresponding curves for the atmospheric-bleeder and the double-pipe condensers, taken from Bulletin No. 171, have been added for the purpose of comparison. These curves are representative of similar curves for other initial temperatures, and it may be observed that the surface of the double-pipe condenser was slightly more effective than that of the other two, but that even the radically different arrangement of surfaces as represented by the different types of condensers has no very decided effect on the performance when reduced to unit bases. Furthermore, for condensers having the same amounts of condensing surface, approximately the same total tonnage may be expected to be developed for any given initial temperature of

water available, when it is possible to circulate the same amount of water per unit of surface.

A comparison of Figs. 3, 7, and 11 indicates that at a given water rate, as the condensing surface was decreased, a greater mean temperature difference between the water and the ammonia was required to maintain a given condenser tonnage. In order to obtain the greater mean temperature difference under these conditions it was necessary to employ water having a lower initial temperature. The latter may be observed by comparing Figs. 2, 6, and 10.

In the vertical shell-and-tube condenser most of the condensation occurs near the top of the tubes, and the liquid ammonia flows down over the remaining surface in a layer that progressively increases in thickness. There is no indication that the level of the liquid in the bottom of the shell rises above the level of the drain pipe, but that the resistance of the liquid layer materially affects the rate of heat transfer may be proven by comparison of the curves in Figs. 4, 8, and 12. At a given water rate the value of K decreases as the tonnage is increased. This indicates that, irrespective of the arrangement or proportions of the condensing surface, as the rate of condensation increases, the thickness of the layer of liquid ammonia adhering to the surface of the tubes increases at such a rate that its resistance more than offsets the tendency of K to increase with increasing values of θ_m . In this respect the heat transmission from a condensing medium to water differs from the transmission from one homogeneous medium to another, in which case K is always observed to increase with increasing values of θ_m .

In Figs. 4 and 12 straight line relations are indicated while in Fig. 8 the lines have distinct curvature. This condition is probably caused by the fact that for Series C and E the geometrical proportions of the condenser were practically the same, while for series D these proportions were different from those in Series C and E. Apparently the arrangement of surfaces has some influence on the relations existing between the coefficient of heat transfer, the water rate, and the rate of condensation.

Further comparison of Figs. 4, 8, and 12 shows that when the tubes were reduced in length a comparatively great decrease in K occurred for a given water rate and condenser tonnage. At the same water rate and condenser tonnage a corresponding decrease in K was not obtained when the surface was further decreased by reducing the number of tubes. This condition may be accounted for by the fact that a large amount of surface was inactive in the tests of Series C,

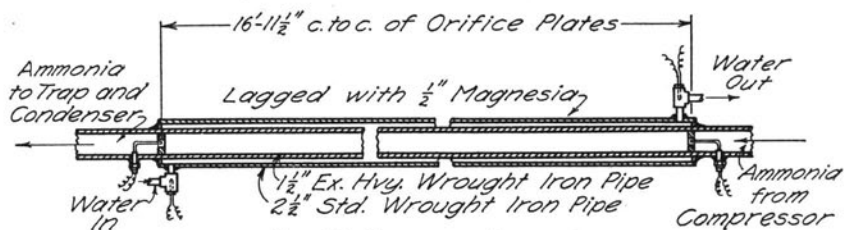


FIG. 16. SUPERHEAT REMOVER

and the first reduction in surface merely eliminated the inactive part, while the second reduction was made at the expense of active surface.

III. TESTS ON SUPERHEAT REMOVER

10. *Description of Apparatus.*—The superheat remover used for this investigation was of the double-pipe type, and consisted of a single $1\frac{1}{2}$ -inch extra heavy pipe practically 17 ft. long, enclosed by a $2\frac{1}{2}$ -inch standard pipe of the same length, as shown in Fig. 16. The outside surface was covered with $\frac{1}{2}$ -inch of magnesia lagging. The superheated ammonia gas passed through the inside pipe, and water was circulated in the annular space between pipes in the opposite direction to the flow of the ammonia. An orifice having a diameter of 0.6 inch was installed at the entrance, and a similar orifice at the exit of the superheat remover, as indicated in Fig. 16. The thermocouples for measuring the temperature of the superheated ammonia gas were placed with the junctions at the centers of the two orifices. These thermocouples were enclosed in small copper tubes. Figure 16 shows the method of installing the tubes so that about 5 inches extended along the axis of the pipe and gave sufficient immersion for the thermocouple leads to eliminate the effect of conduction of heat from the junctions. The orifices tended to break the stream lines and gave a high velocity to the gas, thus insuring that the reading of the thermocouples were indicative of the average temperature of the gas. The thermocouples for observing the temperature of the water at entrance and exit were placed in glass tubes and surrounded by oil. These tubes were then placed in tees as shown in Fig. 16 so that the tubes extended about 5 inches along the axis of the pipes into the stream of water.

The plant and weighing system were the same as those used for the tests on condensers, and have been fully described in Engineering Experiment Station Bulletin No. 171.

11. *Method of Conducting Tests.*—The superheated ammonia gas after leaving the superheat remover passed into a condenser, and the condensate was weighed in drums placed on platform scales. The cooling water was weighed in tanks placed on platform scales.

For all tests the pressure of the ammonia gas was maintained constant at approximately 147 lb. per sq. in. gage. The initial temperature of the gas was maintained at approximately 165 deg. F. and the final temperature at about 125 deg. F. The weight of ammonia was varied from 4.25 lb. per min. to 6.5 lb. per min.

The initial temperature of the cooling water was controlled so that it was always higher than the saturation temperature for ammonia vapor corresponding to the observed pressure, in order to insure that no condensation occurred in the superheat remover. The weight and initial temperature of the water were then adjusted so that, with the various combinations of weight and initial temperature, the temperature of the ammonia gas leaving the superheat remover was approximately 125 deg. F.

12. *Results of Tests.*—The results of the tests on the superheat remover are given in Table 3.

The mean temperature difference between the ammonia gas and the water is given in column 9. This difference varied from 34.7 to 52.2 deg. F. and was calculated directly from the formula:

$$\theta_m = \frac{\theta_1 - \theta_2}{\log_e \frac{\theta_1}{\theta_2}} \quad (3)$$

in which θ_m = mean temperature difference between the ammonia and the water, deg. F.

θ_1 = difference between the final temperature of the ammonia and the initial temperature of the water, deg. F.

θ_2 = difference between the initial temperature of the ammonia and the final temperature of the water, deg. F.

The heat transferred per minute from the ammonia to the water is given in column 10. This heat could be computed either from the weight and drop in temperature of the ammonia, or from the weight and rise in temperature of the water. It was found that the heat given up by the ammonia never differed by more than 5 per cent from the heat absorbed by the water. Hence the average of these two was

TABLE No. 3
PRINCIPAL RESULTS OF TESTS ON DOUBLE-PIPE SUPERHEAT REMOVER

Test No.	Ammonia lb. per min.	Water lb. per min.	Average Ammonia Pressure lb. per sq. in. abs.	Initial Ammonia Temperature deg. F.	Final Ammonia Temperature deg. F.	Initial Water Temperature deg. F.	Final Water Temperature deg. F.	Average Temperature Difference deg. F.	Average Amount of Heat Transferred B.t.u. per min.	Coefficient of Heat Transfer B.t.u. per sq. ft. per hr. per deg. F.	Average Ammonia Velocity ft. per sec.	Average Water Velocity ft. per sec.
1		3	4	5	6	7	8	9	10	11	12	13
1S	4.44	12.10	161.0	167.8	119.3	93.6	105.5	41.4	142.2	30.99	13.11	0.239
2S	4.31	13.69	160.7	168.7	120.7	95.3	105.7	41.4	137.7	30.01	12.81	0.270
3S	4.27	18.75	160.6	168.2	118.8	95.1	103.0	41.1	142.5	31.29	12.67	0.370
4S	4.42	22.20	161.0	167.9	120.0	98.8	104.9	38.4	136.5	32.08	13.09	0.438
5S	4.42	27.80	162.1	168.1	121.3	103.2	107.6	35.1	128.1	32.93	13.02	0.548
6S	5.22	10.71	161.5	164.8	120.6	88.5	103.6	45.2	156.5	31.24	15.39	0.211
7S	5.32	12.64	162.3	165.3	119.3	87.5	100.7	46.2	163.0	31.84	15.55	0.249
8S	5.19	14.84	161.5	165.4	118.6	88.7	99.5	45.7	159.4	31.47	15.27	0.293
9S	5.24	15.95	161.5	166.6	120.5	92.2	102.1	44.0	157.2	32.24	15.45	0.315
10S	5.15	22.85	162.4	167.7	121.6	96.9	103.7	41.3	153.8	33.60	15.11	0.451
11S	5.19	29.80	162.4	168.0	121.0	98.4	103.6	39.9	156.6	33.42	15.25	0.588
12S	6.14	7.78	163.7	167.4	120.4	98.2	114.1	44.5	158.9	33.14	18.07	0.153
13S	6.07	18.23	164.2	168.8	127.3	105.7	107.5	42.3	158.4	33.70	17.72	0.408
14S	6.21	20.70	163.7	168.3	130.0	106.6	112.6	37.2	153.4	34.69	17.88	0.458
15S	6.08	23.20	163.7	168.3	129.6	108.6	112.7	36.1	141.7	33.42	17.50	0.542
16S	5.97	27.50	164.0	168.5	130.0	108.7	113.8	38.7	139.2	33.20	19.33	0.277
17S	6.62	11.34	163.2	165.0	123.2	95.8	102.7	48.9	181.1	33.42	18.36	0.327
18S	6.59	12.00	162.3	164.1	123.6	97.8	102.7	47.5	173.9	33.42	19.33	0.327
19S	6.68	16.20	162.6	165.3	124.5	91.7	103.1	46.0	140.1	33.33	18.56	0.320
20S	6.44	21.40	163.4	166.6	123.8	92.7	101.2	46.3	181.7	35.41	18.80	0.432
21S	6.51	26.55	164.5	168.0	126.0	92.7	104.9	43.1	176.9	37.04	19.00	0.324
22S	6.68	14.89	162.4	168.8	124.2	86.1	99.6	52.2	203.0	35.09	19.42	0.294

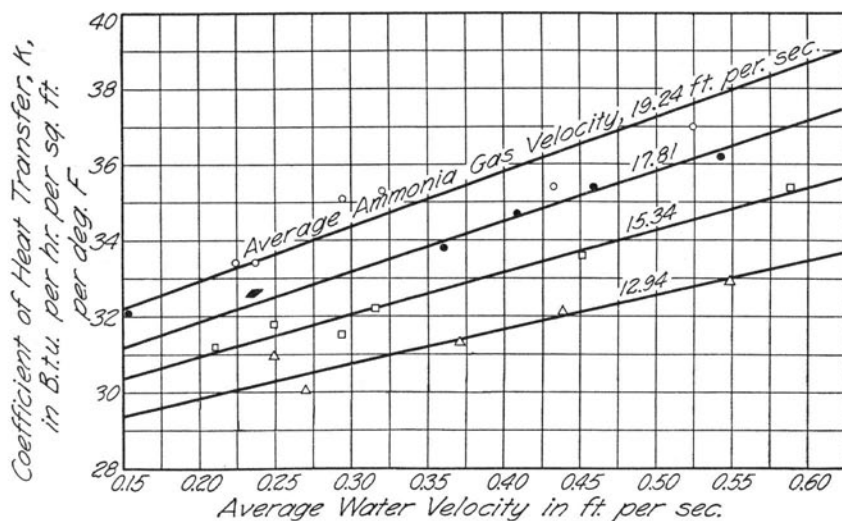


FIG. 17. COEFFICIENT OF HEAT TRANSFER FOR SUPERHEAT REMOVER

considered as being representative of the true heat transfer, and has been tabulated in column 10. The fact that the difference between the heat given up by the ammonia and that absorbed by the water never exceeded 5 per cent, and that this difference was sometimes positive and at other times negative, was accepted as an indication that no liquid was carried into the superheat remover, and that no condensation occurred. The possibility of condensation occurring was minimized by maintaining the initial temperature of the water well above the saturation temperature of the ammonia. In this way the temperature of all surfaces with which the superheated ammonia gas could come into contact was above the dew point corresponding to the pressure within the superheater.

The velocity of the water given in column 13 was computed directly from the weight of water flowing per second and the cross-sectional area of the annular space between the pipes. The velocity of the superheated ammonia gas given in column 12 was computed in the same manner, and was based on the arithmetical mean between the specific volumes of the gas at entrance to and exit from the superheat remover.

The values of K , given in column 11, were computed from the formula

$$K = \frac{60 H}{A \theta_m} \quad (4)$$

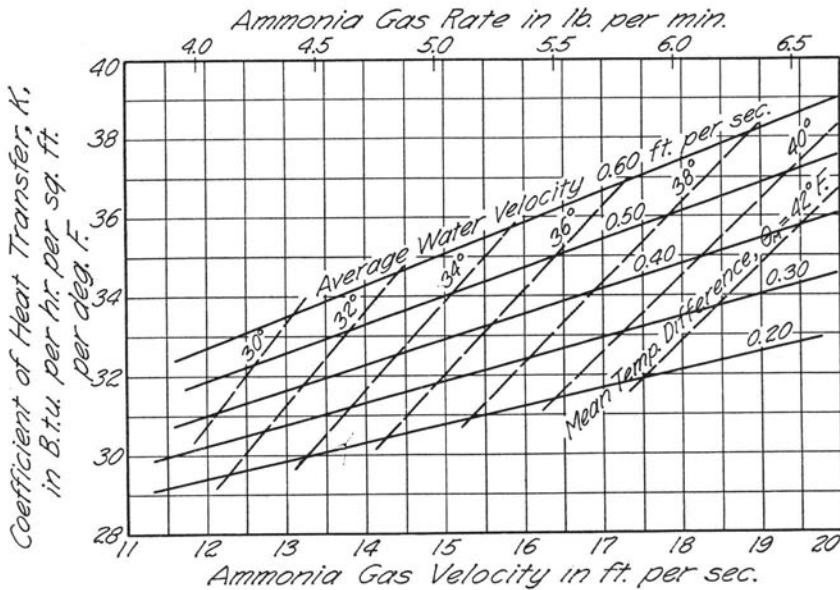


FIG. 18. PERFORMANCE CHART FOR SUPERHEAT REMOVER

in which K = mean coefficient of heat transfer, or the B.t.u. transferred per sq. ft. per hr. per deg. difference in temperature.

H = heat transferred from the ammonia to the water (col. 10) B.t.u. per min.

A = internal area of the inside pipe = 6.65 sq. ft.

θ_m = logarithmic mean temperature difference between the ammonia and the water (col. 9), deg. F.

The relation between the coefficient of heat transfer, the velocity of the water, and the velocity of the ammonia gas are shown in Fig. 17 which has been plotted from the observed data. Apparently for a given velocity of ammonia, K is a linear function of the velocity of the water. It may be noted, however, that all of the water velocities are low, and are probably all within the range of viscous flow. With the apparatus under consideration it was not possible to obtain values within the range of turbulent flow, and hence no predictions can be made regarding the relations existing under these conditions.

Figure 18 is a performance chart for the superheat remover, and has been derived from Fig. 17 and Equation (4). It was found possible

to represent all relations by means of straight lines on this chart, and it may also be noted that for a given velocity of the water K is a linear function of the velocity of the ammonia.

IV. CONCLUSIONS

13. *Conclusions.*—As a result of this investigation the following conclusions may be drawn:

(1) The thickness of the layer of liquid ammonia adhering to the tubes of the vertical shell-and-tube condenser materially affects the rate of heat transfer per unit of surface.

(2) At a constant water rate the coefficient of heat transfer decreases with increasing values of the mean temperature difference between the ammonia and the water in the vertical shell-and-tube condenser.

(3) Irrespective of the proportions of the vertical shell-and-tube condenser no appreciable subcooling of the liquid occurs.

(4) The condenser tonnage developed per square foot of surface in the shell-and-tube condenser is independent of the size or proportions of the condenser as used in this investigation and is a function only of the initial temperature of the water and the amount circulated per square foot of surface per unit of time.

(5) The condenser tonnage developed per square foot of surface in the different types of condensers as used in this investigation is approximately the same regardless of proportions or arrangement of surface if a given amount of water at a given initial temperature is circulated per square foot of surface in a given time.

(6) One square foot of surface is approximately eight times as effective in transferring heat from saturated ammonia vapor to water as it is in transferring heat from superheated ammonia gas to water.

(7) For conditions of viscous flow on the water side the coefficient of heat transfer in a superheat remover is a linear function of the water velocity.

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DAVID KINLEY, Ph.D., LL.D., President

THE UNIVERSITY INCLUDES THE FOLLOWING DEPARTMENTS:

The Graduate School

The College of Liberal Arts and Sciences (Curricula: General with majors, in the Humanities and the Sciences; Chemistry and Chemical Engineering; Pre-legal, Pre-medical and Pre-dental; Pre-journalism, Home Economics, Economic Entomology and Applied Optics)

The College of Commerce and Business Administration (Curricula: General Business, Banking and Finance, Insurance, Accountancy, Railway Administration, Railway Transportation, Industrial Administration, Foreign Commerce, Commercial Teachers, Trade and Civic Secretarial Service, Public Utilities, Commerce and Law)

The College of Engineering (Curricula: Architecture, Ceramics; Architectural, Ceramic, Civil, Electrical, Gas, General, Mechanical, Mining, and Railway Engineering; Engineering Physics)

The College of Agriculture (Curricula: General Agriculture; Floriculture; Home Economics; Landscape Architecture; Smith-Hughes—in conjunction with the College of Education)

The College of Education (Curricula: Two year, prescribing junior standing for admission—General Education, Smith-Hughes Agriculture, Smith-Hughes Home Economics, Public School Music; Four year, admitting from the high school—Industrial Education, Athletic Coaching, Physical Education. The University High School is the practice school of the College of Education)

The School of Music (four-year curriculum)

The College of Law (three-year curriculum based on two years of college work.

For requirements after January 1, 1929, address the Registrar)

The Library School (two-year curriculum for college graduates)

The School of Journalism (two-year curriculum based on two years of college work)

The College of Medicine (in Chicago)

The College of Dentistry (in Chicago)

The School of Pharmacy (in Chicago)

The Summer Session (eight weeks)

Experiment Stations and Scientific Bureaus: U. S. Agricultural Experiment Station; Engineering Experiment Station; State Natural History Survey; State Water Survey; State Geological Survey; Bureau of Educational Research.

The Library collections contain (June 1, 1927) 733,580 volumes and 162,783 pamphlets.

For catalogs and information address

THE REGISTRAR

Urbana, Illinois

